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ABSTRACT

Presented are seven articles (reprinted from "The Exploratorium" magazine) which focus on the scientific explanations for the specific (and oftentimes peculiar) instructions and procedures called for in many recipes. "Baking, Boiling, and Other Hot Topics" (Joel Myerson) discusses different methods of cooking. "The Culinary Alchemy of Eggs" (Arthur E. Grosser) discusses the chemistry of eggs and whether it is necessary to put salt in water when hard-cooking an egg. "To Do and Notice: Meringue Science" (Rob Semper) examines why egg yolks should not be mixed with egg whites when preparing meringue. "To Do and Notice: The Annotated Lemon Meringue Pie" (Pat Murphy) provides a recipe for making a lemon meringue pie, together with explanations for the recipe's procedures. "To Do and Notice: Taking an Egg for a Spin" (Rob Semper) tells (in terms of physics) how to decide if an egg has been hard-boiled. "On the Rise" (Linda Dackman) discusses the biology (yeast), chemistry (carbon dioxide production, gluten production, and acid/base balance), and physics (convection currents and the relationship between incident radiation and baking pan materials) of baking bread. A recipe for baking whole wheat bread is presented in the final article "To Do and Notice: Whole Wheat Bread" (Linda Dackman). (JN)

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Cooking and Science

Introduction

by Pat Murphy

Editor, *The Exploratorium* magazine

I have always felt that cookbooks make arbitrary and unreasonable demands of the cook. Recipes call for strict adherence to a set of peculiar instructions and arcane procedures, but they rarely explain the reasoning behind their dictates. The recipe for a lemon meringue pie insists that the eggs for the meringue must be at room temperature. Instructions for hard-boiling an egg tell you to start the egg in cold water. Cake recipes tell you to reduce your baking time or temperature if you use a glass cake pan. Anyone who cooks learns to follow the rules, and there are many rules to follow.

Why follow the rules? The proof, as my 7th grade home economics teacher once told me, is in the pudding. If you don't follow the instructions, the end product will be inedible or at least unappetizing. This reason, though valid, is hardly satisfying.

The articles in this issue of *Ideas in Science* are taken from a special issue of *The Exploratorium* magazine on the topic of cooking. When we set out to do a magazine on cooking, we sought out more satisfying answers. In the course of our investigation, we realized that many of the cookbook's demands are not arbitrary at all. The articles reprinted here consider only a few of the cookbook's many questionable dictates. We realize that this is just a beginning and hope that reading about our investigations in the kitchen will encourage you to experiment and question on your own.

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Baking, Boiling, and Other Hot Topics

by Joel Myerson

Look in any cookbook and there will be recipes for simmering, poaching, boiling, steaming, broiling, roasting, frying, sautéing, and so on. The methods seem limited only by the imagination of the recipe makers and the cookbook writers. All these cooking methods transfer heat from the heat source to the food, changing the food from raw to cooked. They differ mainly in how this is done, and how fast.

Getting Heat from Here to There

Consider your basic chicken recipe: put a chicken in the oven at around 350°F and bake until done. When you turn on the oven, the gas flame or electric heating element heats the air surrounding it and the hot air circulates in the oven. When molecules of air absorb heat, they become more agitated and contain more energy than when they were cool. The molecules of hot air smash into the surface of the chicken; the chicken absorbs some of their energy and gets hot, while the air molecules lose energy and become cooler.

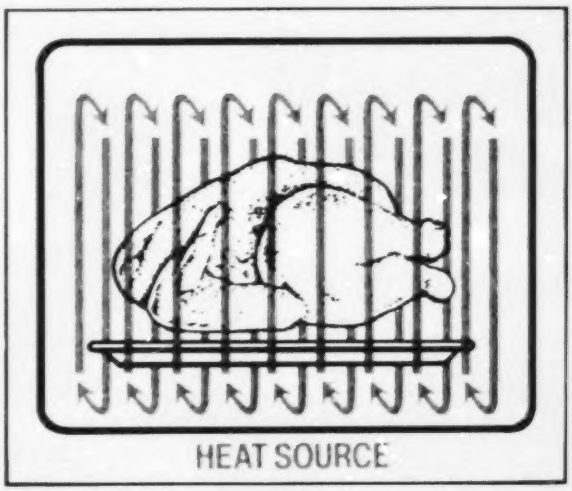
In your oven, the circulation of hot air is caused by a process known as convection.* The lighter, less dense hot air floats upward and transfers some of its heat to the food and to the oven walls. The resulting cooler air then sinks to the oven floor to be reheated.

In convection, the air acts as a heat transfer medium that moves heat from the heat source to the vicinity of the chicken. The actual heating of the chicken occurs via conduction, by direct contact of the hot air with the chicken. In conduction, each molecule transfers heat energy to adjacent molecules by colliding with them.

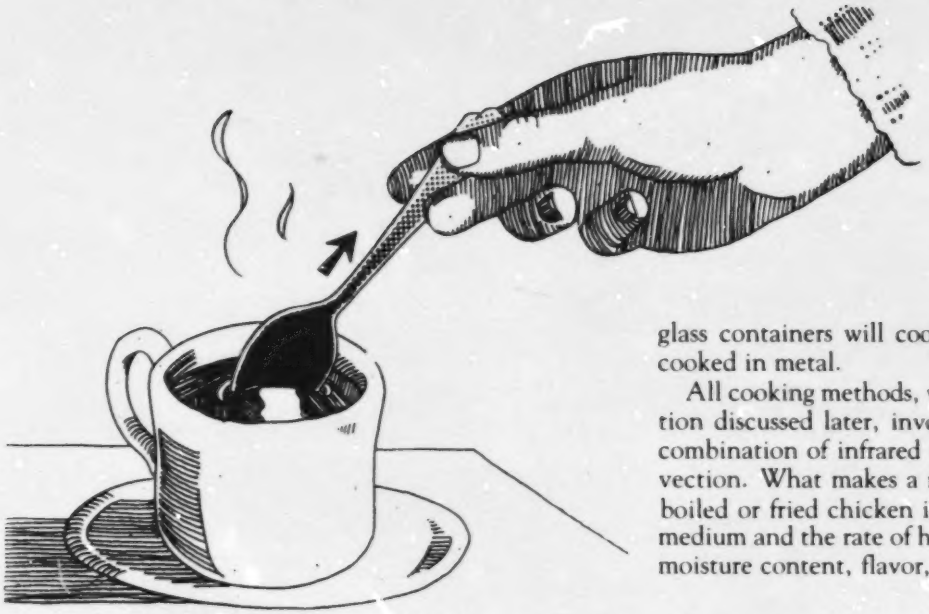
* Ironically, the so-called convection ovens shorten cooking time by circulating hot air with a fan, rather than relying on convection.

A metal spoon in a cup of hot coffee is warmed by conduction. The hot coffee warms the bowl of the spoon, and the metal conducts the heat up into the handle. Similarly, the hot air warms the outside of the chicken and the meat conducts the heat toward the colder inside.

If you were to try to cook a whole chicken at 500°F (about 200°C), the outside would burn while the inside remained raw. The surface heat would not be conducted to the inside fast enough to cook it before the outside started to burn. When your cookbook says to cook a whole chicken at 350°F for 20 minutes per pound, the advice takes into account how long it takes for heat to be conducted from the surface of the chicken to the center. Obviously, this depends on the distance from the surface to the center, and a chicken cut up into small pieces will cook faster than a whole bird.



In your oven, the heating element warms the air that surrounds it. Since hot air is less dense than cold air, the hot air surrounding the heating element rises. These air molecules lose heat when they bump into the chicken and the oven walls, cool down somewhat, and sink back down to the oven floor to be reheated. This process, known as convection, keeps the heat circulating in your oven.



When you put a spoon into a cup of hot coffee, you are bringing the agitated and energetic molecules of the hot coffee into contact with the relatively lethargic molecules of the cooler spoon. The molecules of the coffee smash into the molecules of the spoon, transferring some of their agitation and warming the spoon. The molecules of the spoon bump into each other, gradually conducting the heat up the handle of the spoon.

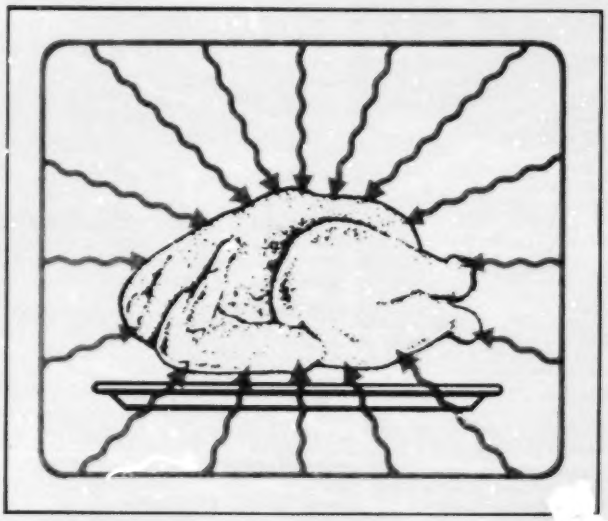
Not all materials conduct heat at the same rate. Since metals are the best heat conductors available, skewering a potato with a nail will shorten the baking time considerably. The nail conducts the heat rapidly to the inside, and the potato cooks from the inside out, as well as the outside in.

Compared to conduction, convection is a relatively fast way to transport heat through a gas. If we took our standard oven and put it into an orbiting space restaurant, our chicken would take much longer to cook. In a zero-gravity environment the driving force for convection, the weight difference between hot and cold air, does not exist. However, the air molecules could still transfer their heat energy to adjacent air molecules by bumping into them — all the way from the heat source to the chicken. A commercial convection oven would be a tremendous help in a zero-gravity restaurant.

The cooking time in an oven, zero-gravity or otherwise, would be even slower were it not for the heat transferred by infrared radiation. This invisible radiation with a wavelength slightly longer than that of red light is what makes you feel warm when you are standing in the sun, even when the air temperature is below freezing. When the sun goes behind a cloud, that warm feeling quickly goes away because the cloud blocks most of the infrared radiation. As much as 75% of the heat that cooks the food in an oven comes from radiation from the hot oven walls.. Compared to infrared radiation, convection and conduction are relatively inefficient methods of heat transfer.

Shiny metal reflects infrared rays. That's why you can keep your chicken from browning too much by placing it under an aluminum foil tent. Glass is reasonably transparent to infrared radiation, which is why foods cooked in glass containers will cook in a shorter time than foods cooked in metal.

All cooking methods, with one high-technology exception discussed later, involve transferring heat through a combination of infrared radiation, conduction, and convection. What makes a roasted chicken different from a boiled or fried chicken is the differences in heat transfer medium and the rate of heating, which affect the texture, moisture content, flavor, and appearance.



Your hot oven walls radiate infrared radiation, a traveling energy wave, generated by the vibration of molecules. When infrared radiation strikes anything—such as the oven walls, the chicken, or the pan beneath the chicken—the molecules of that object absorb the radiation, warm up, and radiate more infrared radiation.

Cooking with Gas

At first glance, baking and steaming seem to be quite different, but they really have a lot in common. They both use a gas as a heat transfer medium.

The water molecules in a steamer are analogous to the air molecules in an oven. In a steamer, the water molecules are at 212°F (100°C), the boiling point of water. If the oven were set at that temperature, it would take all day to cook something. So why does food cook so much faster in a steamer?

In an oven, the hot dry air transfers heat to the food and cools off. In the steamer, the steam condenses on the cooler food. Water absorbs heat when it evaporates and releases heat when it condenses. (This is the reason that you cool off when your sweat evaporates.) When the steam

condenses, the heat released is about sixteen times greater than the heat released when an equal volume of hot dry air cools from 212°F to room temperature.

The steam does not necessarily condense every time a steam molecule bumps into the food. The molecules can transfer heat energy by conduction, just as the air does in an oven. One of the factors that determines how much heat a gas can transfer is the amount of heat energy it can contain at a given temperature: its heat capacity. Because the heat capacity of steam is one and one quarter times greater than the heat capacity of dry air, steam will cook food faster even if the steam does not condense.

Water absorbs heat when it evaporates and releases heat when it condenses. When you cook vegetables in a steamer, steam condenses on the vegetables and releases heat. The heat released by condensing steam makes the vegetables cook more quickly than they would in dry air at the same temperature as the steam.

Cooking in Liquids

Cooking methods that use liquid to transfer heat are faster than those that use gas, primarily because a liquid is so much denser than a gas. Hot liquid can circulate by convection, very much like the hot air in an oven, but the hot liquid has many more molecules to transfer heat.

Boiling, poaching, and stewing use water to transfer heat to the food. Deep frying is similar to boiling and poaching, except that it uses oil instead of water. Oil can get hotter than water, reaching temperatures of up to 400°F (about 200°C) before it starts to decompose, smoke, and burn. It can cook the food much faster than water, which at room pressure only reaches a temperature of 212°F (100°C) before it boils.

You can increase the boiling point of water by using a pressure cooker. Each molecule in liquid water is constantly in motion, being buffeted by the molecules around it. This motion creates an internal pressure that pushes the molecules apart. The water is held together by attraction between molecules and by the pressure exerted by the atmosphere, which weighs 15 lbs. per square inch at sea level. When you heat water, the molecules move around more violently. When the temperature reaches 212°F (100°C), their motion creates an internal pressure equal to the external atmospheric pressure, and the water boils. Adding more heat to the water will not raise its temperature; it will just cause the water to boil more vigorously. However, changing the external atmospheric pressure will change the temperature at which water boils. Move to Aspen, Colorado, and you will never drink your coffee any hotter than 198°F, the boiling point of water at 8,000 feet.

At sea level, the little weight on top of your pressure cooker doubles the pressure inside, acting like another 15 lbs. per square inch of atmospheric pressure. As a result, water will not boil until it reaches 250°F, and foods are cooked (and overcooked) much more rapidly.

Cooking by Contact

There are some cooking methods in which the primary heat transfer medium is neither a liquid nor a gas. When a lean steak is put in a hot pan, heat is transferred directly from the pan to the steak surface. Of course, any liquid (such as a thin film of oil) or gas (such as steam or air) that is between the food and the pan will also act as a heat transfer medium and conduct heat through to the steak. Frying an egg or cooking pancakes in a teflon pan without using oil are other examples of cooking by contact.

Cooking with Radiation

You may have wondered why, even though hot air rises, an oven broiler has the heating element on top. Radiative heat transfer does most of the cooking in broiling. Suppose you are broiling a steak. If the heating element were below the steak, the pan holding the meat would absorb the radiation and it would not reach the steak. As long as there is nothing between the food and the heat source, the location of the heat source does not matter, since radiation travels in all directions from the source. In fact, a barbecue grill uses infrared radiation coming from below the food, and a toaster directs it from the sides.

Have you ever tried to broil a whole chicken or roa

When you fry food, the hot oil is in direct contact with the food. Heat is transferred from the oil to the food by conduction, and the food heats quickly.

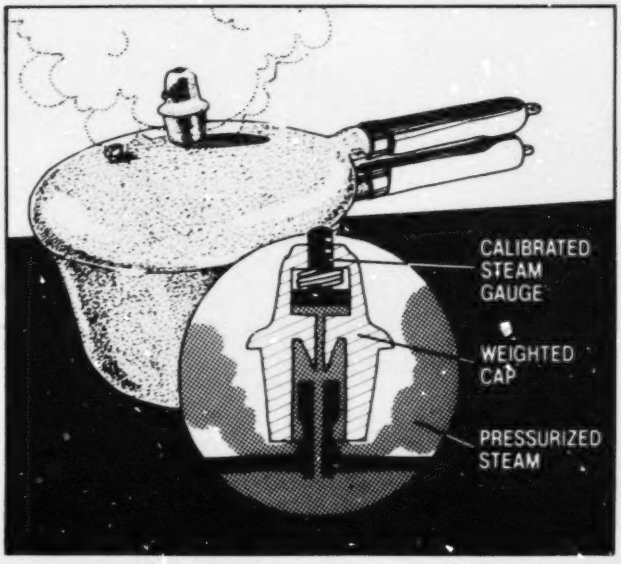
At the Exploratorium, you can watch the currents generated by temperature differences at an exhibit called Convection Currents. The heated tip of a rod warms the liquid. Since hot liquid is less dense than cooler liquid, the hot liquid surrounding the tip of the rod rises, creating patterns of turbulence. When you heat chicken noodle soup on a range, the soup at the bottom of the pan absorbs heat from the pan and rises, which mixes the soup. When you heat a thicker liquid—split pea soup, for instance—the movement of the hot liquid is slow enough so that the heat cannot circulate easily. Frequent stirring, which substitutes for the convective currents, is advisable unless you wish to sacrifice your soup to the cause of science.

beef? Broiling works best with meat that is not too thick, because the intense, unidirectional heat can burn the outside before the inside is cooked. A rotisserie solves this problem by rotating the food to give it an even radiation bath.

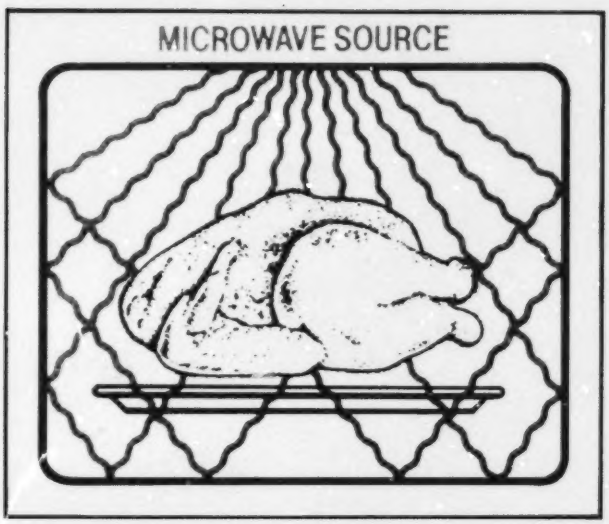
Cooking with Microwaves

Infrared radiation is not the only type of radiation that will cook food. Microwave cooking, a method that is fundamentally different from any other method of heat transfer, has become very popular in recent years. Other cooking methods bring heat to the surface of the food, which conducts it inward; microwave radiation penetrates the food and cooks it uniformly. Or would cook it uniformly, if the food were uniform. Those of you with microwave ovens may have noticed that curious things can happen to some foods. Apple pie, for example, turns to mush before the crust cooks at all.

Microwave radiation is absorbed by certain molecules in the food, particularly water molecules. Absorbing microwaves causes water molecules to get hot, move around, and heat up the surrounding area. Since not all foods contain the same amount of water, different foods absorb microwaves at different rates. The apples in the pie have a high water content and soak up the microwave energy, while the crust, which has very little water, hardly cooks at all.



The boiling temperature of water depends on the surrounding air pressure. At sea level, atmospheric pressure is about 15 lbs. per square inch and water boils at 212°F.The weighted cap on top of your pressure cooker regulates the pressure inside the pot. Using a pressure cooker at 15 lbs., you double the atmospheric pressure. At this pressure, water boils at 250°F. Since the water temperature inside a pressure cooker is higher than it would be in an open pot, the food cooks faster.



Like infrared radiation, microwave radiation is a traveling energy wave. Microwave radiation is absorbed by molecules in food, particularly hot water molecules. When water molecules absorb microwave radiation, they heat up. Since not all foods contain the same amount of water, foods heat at different rates in a microwave oven.

Glass, paper, and some plastics absorb very little microwave energy, which is why you can use them as cooking containers. Metal reflects the microwaves, which prevents the food inside a metal container from being cooked and also creates electrical fireworks in the oven.

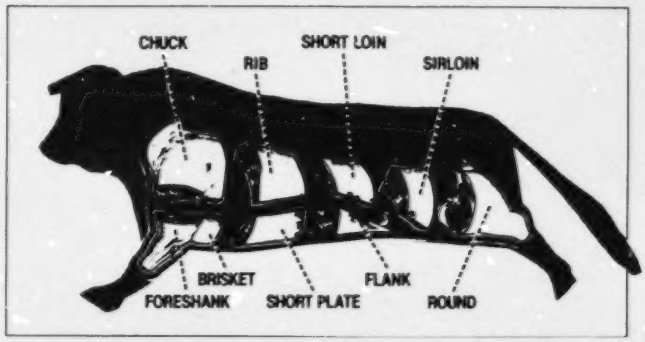
What Difference Does It Make?

Given that all cooking methods involve transferring heat to food, why would you choose one method over another? If you have ever tried to cook a chuck steak and a porterhouse steak both on your barbecue grill and in your stew pot, you will have chewed your way through two important lessons: 1) Different cooking methods have different effects on tenderness, and 2) If you have enough money to buy the most expensive cuts, your cooking methods don't matter as much.

Connective tissue is what holds muscle fibers together. The more connective tissue, the tougher a piece of meat will be. Connective tissue is much more prevalent in muscles that are used frequently, and it increases with the age of the animal, which is why those old stewing chickens are tough.

When meat is cooked, the muscle fibers themselves have a tendency to harden. However, connective tissues tend to break down, particularly when meat is cooked with moist heat. The moisture helps to chemically change the collagen in the connective tissue into gelatin. A good rich meat broth, in which the meat has literally fallen off the bones, solidifies when it cools, due to the gelatin formed during cooking. Moist heat methods, such as boiling, simmering, poaching, stewing, steaming, and braising, help tenderize less expensive, tougher cuts of meat.

The same factors that build connective tissue in animals — that is, age and exercise — also increase flavor. Not only is it a waste of time to use porterhouse steak in your beef stew, it won't even taste as good. Of course, cooking the porterhouse steak over a barbecue grill makes a tender, tasteful meal. The small amount of connective tissue ensures tenderness, the fat adds flavor and helps prevent the meat from drying out, and the grill's high temperature encourages many complicated chemical reactions to occur on the meat's surface.



Tenderness and flavor of a piece of meat is determined by the age of the animal and the cut of meat. The connective tissue that holds muscle fibers together also makes meat tough. Age and exercise, factors which build connective tissue, also increase the meat's flavor.

Chief among these reactions is browning, known as the Malliard reaction, after the scientist who first studied the phenomenon. The surface of meat browns when naturally-occurring sugars react with proteins. By basting meat with barbecue sauce or some other liquid that contains sugar, you can encourage the browning reaction. The Malliard reaction is also responsible for the golden brown color of french fries and the brown crust on baked bread.

Many of the flavor compounds that we associate with foods are formed during the cooking process. The characteristic odors of roast beef and freshly baked bread, for example, are not produced until the food is cooked. The flavor, as well as the texture and appearance, are affected by the temperature and the cooking method. The crisp crust on baked bread does not form on steamed buns served in Chinese dim-sum restaurants, french fries do not resemble boiled potatoes, and chicken stew is no substitute for fried chicken.

Whether you roast or steam, boil or deep fry, broil, barbecue, or microwave your chicken, understanding how cooking methods differ should make it easier to figure out why your chicken came out brown and crisp, pale and limp, or burnt and dried out. □

The Culinary Alchemy of Eggs

Why add salt — and other vexing matters

by Arthur E. Grosser

How often do American scientists prove of value putting together a dinner? Are we just substitutes for a food processor — cutting, peeling, slicing, shredding, chopping, grating — all with our gray matter on standby? Not too pleasant a way to spend time. And what about following recipes? They are just a series of imperative statements, orders without justifications, treating us like Marine recruits. It would be more fun to be able to use our heads while we cook.

But can it be done? I did not know until I tried to figure out why I kept on doing what my mother had told me all those years ago when I was six: to put salt in the water when hard-cooking an egg. (Because the water should not be boiling while the egg cooks, "hard-cooking" is a more accurate term than "hard-boiling.") I went to a good cookbook and checked out the recipe. It looked something like this:

Hard- or Soft-Cooked Eggs
(one serving)

2 eggs at room temperature
1 quart cold water
2 tablespoons salt

Make a hole in the large end of each egg. The hole should be 1/16 inch in diameter. Put the eggs in a pot with the water and salt. Add more water (and salt) if necessary, to cover the eggs. Heat the pot until the water boils, then reduce the heat so that the water simmers.

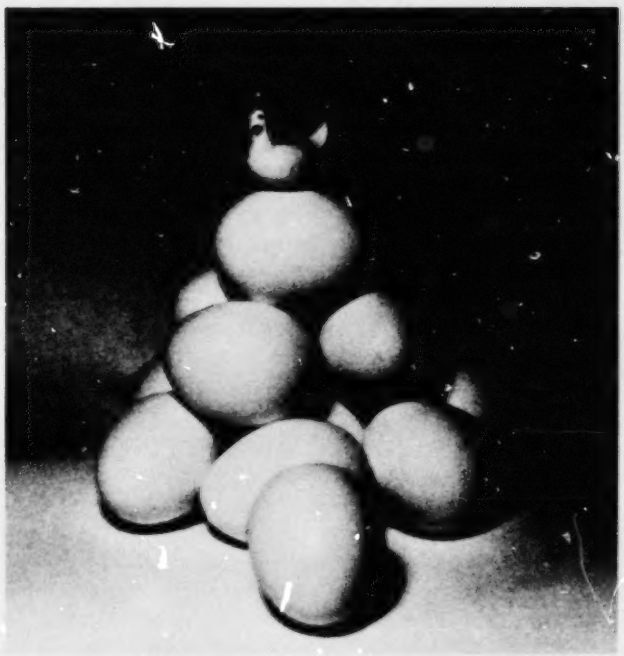


Photo by Marcia Daniel

Cook 2 to 3 minutes for soft-cooked, and 10 to 12 minutes for hard-cooked. Immediately remove the pot from the heat, put it in the sink, and let cold water run into it until the eggs are cool enough to handle. Shell them and serve.

When you heat an egg in the shell, the air inside expands. If you make a hole in the large end of the shell, you provide the expanding air with an escape route, and the egg will not crack.

My mind started to boggle. Not only was the salt really in the recipe (for no apparent reason), but so were some other unexplained requirements. Why did the eggs have to be at room temperature, and why did the cooking water have to start off cold when I was going to heat it up right away? Why a hole in the egg, and why simmered rather than conveniently boiled? And finally, did the cold-water rinse do any more than make the shelling job less painful on my tender hands? The choice was obvious: either accept the orders and forget the whys, or dig into the reasons. And the most satisfying and generally useful reasons would be molecular.

If a recipe for hard-cooked eggs is any good at all, it will try to keep each egg in one piece and prevent the shell from cracking. Eggs crack because they are built to do so. They carry around a little heat-sensitive detonator. If you want to verify this, here's an experiment to try:

Heat an egg in a pot of cold water and watch the large end. You will see a stream of air bubbles coming through the shell from a pocket of air held captive between the membranes in the egg. Now make a pinhole in the large end of the egg and put the egg back into the pot of (what should be lukewarm) water, continuing to heat it. This time you will see, instead of little bubbles, a jet of air expelled from the hole.

As the egg heats up, the air inside expands and tries to find a way out of the shell. Cleverly foreseeing this eventuality, the egg has provided itself with an escape hatch: pores in the large end of the shell. The air bubbles you saw in the first part of the experiment had forced their way through these tiny pores. Now a race begins between the buildup of pressure within the egg and its release as the air oozes out. If the air pocket is heated faster than the air can escape through the shell, there is terrific internal pressure, and the shell cracks.

But not every egg, like not every person, will crack under stress. Some eggshells have bigger pores than others, which means they let the air out more readily and are relatively uncrackable. Still other eggs have a fairly small air pocket. Unfortunately, there is no way of knowing which type of egg we have before cooking it, so to make sure the air can get out through the shell before the pressure becomes too great, the recipe has us poke a hole in the large end of the shell.

Not content with attending to the thermodynamics of gases, the recipe is also sensitive to the kinetics of crack-prevention. By starting the eggs in cold water, it ensures that the temperature rises gradually and allows more time for the air to seep out. Reducing the heat to simmering lessens the chance of cracking as well and prevents overcooking, which toughens the white before the yolk has cooked.

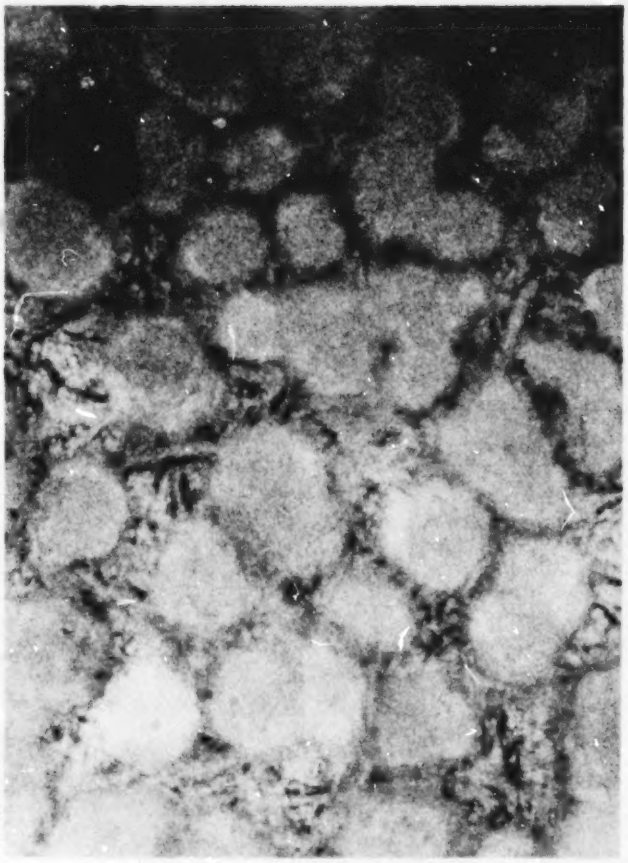


Photo by Jack Daniel

A closer look at an eggshell (magnified 400 times) reveals that the eggshell is not as solid as it might appear to your naked eye. When you heat a whole egg, the air pressure inside the egg increases and air oozes out through the pores in the large end of the shell.

There is an aesthetic bonus hidden here. Egg white cooks very quickly, and if it sets into shape before the air gets out, the shelled egg has a flat end like a boxer's nose. The egg with a pinhole in the shell, on the other hand, mirrors the beautiful ovoid shape of the shell, because the white flows into the space vacated by the escaping air. Of course, a flat bottom may be useful if eggs sitting at attention is what you are after.

Pin-holing is especially important when you are dealing with old eggs. As an egg ages, more air gets into it, and the air pocket enlarges, sometimes enough to make the egg float in water. These floaters are best used for scrambled eggs.

Sometimes it is terribly inconvenient to start eggs in cold water. If the pot is too small to cook them all in one batch, it seems silly to throw out the hot water and start all over again. But an egg started in hot water can bring another cracking mechanism into play — thermal shock.

When an egg straight out of the refrigerator is tossed into boiling water, the different regions of the shell, which are of different thicknesses, cannot expand in unison, and the shell cracks. So, if you must put the eggs in hot water, use the pinhole trick, and then run some warm tap water over them to lessen the shock when they are put in the pot. And then put in some salt! Unreasonable? Illogical?

At first glance it does seem ridiculous. Although air can get in and out of the eggshell, salt cannot, so what effect can it have on the egg snug inside? Salt does raise the temperature of the boiling water a bit, but not enough to be important. And it does not prevent cracking, which can happen to even the best-laid and most apprehensively watched eggs. So why add salt?

Egg Chemistry

Egg white is almost all water (88%) and protein (11%). In its natural state the white is semifluid, and when cooked it becomes firm but resilient. This change mirrors on a visible level the fate of the molecules when we turn up the heat.

An egg protein is a shy molecule, and when left alone it will curl up into itself, coiling into a ball. Held in this shape by very weak chemical bonds inside the ball, it is content to examine its navel and to float serenely around in the 88% sea, without any interest in the other protein balls. This leisured, snobbish existence is destroyed if the temperature is raised.

Then, hordes of water molecules carom off each other and the proteins in frenzied and chaotic collisions. As the temperature increases, the action becomes more energetic until a molecular demolition derby is under way. The weak internal bonds of the egg protein can no longer hold the ball together, and it opens out into a floppy streamer.

Only now do we find the real reason for the protein's solitary behavior. It coiled itself up not from narcissism, but as a defensive maneuver, for when it opens out into a streamer, it exposes a soft underbelly of richly seductive targets for chemical attack and bonding. As these protein streamers bump into each other, they immediately bond and form strong links; others latch on randomly as well, until finally there is a three-dimensional protein network, semirigid and immobile — to our touch, firm and resilient. The difference between the semifluid raw egg and the semirigid cooked one is just the difference between the natural sea state of the protein balls and the network that heating has driven them into.

Not only will high temperature and the consequent molecular massage pummel the solitary protein molecules, opening them up and allowing them to form a network, but so will salt or food acids. Chemical bonds are electrical, and the charged particles from dissolved salt or acid can

In the white of a raw egg, each protein molecule leads a solitary existence, curled up in a ball and held in its coiled state by weak chemical bonds. Heating the egg white agitates all the molecules, bouncing them around and breaking the weak bonds. When the bonds are broken, the proteins uncoil, exposing many sites for new bonds. When these uncoiled proteins bump into one another, they form new bonds, joining together in a three-dimensional protein network.

change the electrical environment of the solitary proteins so much that their weak internal bonds break spontaneously. The proteins then uncoil and enter the dance that leads to the interlocking molecular network. In other words, the protein cooks a lot faster.

This is the reason the dissolved salt or acid in the cooking water helps keep a cracked egg neat — there are no ugly streamers of white floating about. Adding salt makes the cooking water much more efficient and faster at its job. If the egg cracks, the white is cooked at the crack and seals it right away, an instantaneous self-repair job. Salting the water is a sort of first aid for a ruptured egg.

Finally, what about that cold-water rinse after boiling an egg? Couldn't it just be the cookbook writer's sissifying excess, easily eliminated while you get your macho kicks, toughing out the pain as you scrabble off the hot shell? Perhaps so, were there not another pitfall to avoid when hard-cooking eggs — the dreaded green yolk. Indeed, how does a beautiful white and yellow egg get such a bilious coating on its innermost parts?

The egg does it to itself, really, but we help it along with overcooking. As the egg is warmed, a small portion of the protein in the white decomposes, and its sulfur and hydrogen unite to form hydrogen sulfide gas, which has a deservedly bad name as "the smell of rotten eggs." The egg is not rotting, however, just cooking.

This gas generated in the white collects in the coolest part of the egg, which during cooking is in the center, where the yolk is. Yolks contain iron, which has a terrific attraction for sulfur. The iron kicks out the hydrogen and forms solid iron sulfide. This union is so swift and tempestuous that it happens at the first opportunity — when the gas reaches the surface of the yolk and forms the dark iron-sulfide deposit.

You can prevent this unnatural liaison by using the cold-water rinse. This not only prevents overcooking, which gives the reaction more time for dirty work, but also quenches it altogether. After the cooking period, the egg is heated through; by chilling the shell in cold water, we force the hydrogen sulfide gas to collect there, pulling it away from the iron-laden yolk.

After all is said and done, there is one big advantage — in addition to educating and impressing your friends, and figuring out how to ad-lib around recipes — that is gained by explaining all these things in the kitchen: your listeners may not notice that you are not doing your share of the work. □

Educated at Cornell University and the University of Wisconsin, Arthur E. Grosser is at present Associate Professor of Chemistry at McGill University. His recent research has been in molecular beam kinetics, educational technology, popular science, and the history of science. The material in this article is adapted from his recent book *The Cookbook Decoder, or Culinary Alchemy Explained* (Beaufort Books, 9 E. 40th St., New York, NY 10016). Address: Department of Chemistry, McGill University, 801 Sherbrooke St. W., Montreal, Quebec, Canada H3A 2K6.

To Do and Notice: Meringue Science

by Rob Semper

As any cook who has tried to make lemon meringue pie knows, the trickiest part is beating the egg whites. Too little beating and the meringue is flabby and lifeless; too much beating and the meringue is tough and flat. But the biggest problem of all is addressed by the warning that is printed in big letters in the cookbook: MAKE SURE THERE ARE NO EGG YOLKS MIXED WITH THE EGG WHITES.

You can try a little experiment to see how deadly the egg yolks can be to a fluffy meringue. Whip the whites of three eggs, one at a time. For the first one, separate the egg yolk from the egg white as carefully as you can and whip for four minutes. Notice how much meringue you have created. Now for the second egg, add a tiny bit of egg yolk, enough to cover your little fingernail. Whip for four minutes again and notice how much less meringue you produce. Finally, for the third egg, add a tiny bit of butter or oil to the egg whites and whip it up. The volume of the meringue will be substantially less.

What is going on here? Why does a little bit of egg yolk ruin the whites? And why do the cookbooks go to such lengths to warn you to avoid whipping egg whites in plastic containers?

When you beat egg whites, you are mechanically performing the same task that the heat does during cooking. The whisk pummels the protein molecules in the egg white, causing them to unravel from their natural coiled state. This process is called denaturing the protein. In its unravelled state, the protein exposes locations that are very receptive to bonding with other protein molecules. As the beating continues, the protein molecules open up more and more and begin to link up with each other, forming a net which traps the air bubbles brought in by the whisk.

When you cook a meringue, the air bubbles expand just as they do in baking bread. For this expansion to happen, the net of proteins must be flexible. As heating continues, the protein net solidifies and the holes formed by the bubbles are baked in.

Too little beating of the egg whites means that the proteins do not open up enough to expose a lot of sites to their neighbors for bonding. This creates a runny mess which cannot trap the air, producing a flabby meringue. Too much beating causes the proteins to unravel too much, creating strong bonds between molecules. This makes the meringue rigid. During cooking, the protein net cannot expand and the bubbles burst, leaving a flat, tough meringue.

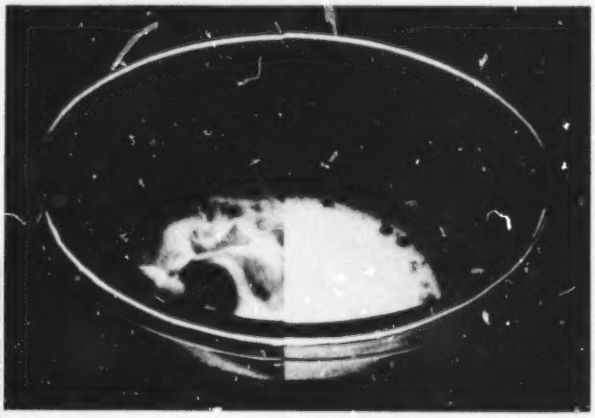


Photo by Juan Venticinque

Compare the meringue produced by egg whites contaminated by a touch of egg yolk (right) and the meringue produced by yolk-free egg whites. The fat in egg yolk prevents the formation of the protein bonds that make a meringue fluffy.

Egg yolk contains fat molecules which attach to some of the bonding sites on the protein molecule of the egg white. These sites then cannot be used for bonding one protein to another and the meringue structure is weaker. It is amazing how little fat is needed to ruin a meringue. Even the residual fat that clings to a bowl after washing can cause problems. Plastic holds onto the fat molecules quite well and is hard to get really clean, which is why many cookbooks tell you not to use plastic bowls for beating eggs. You can make a good meringue in a copper or a stainless steel bowl. Many cookbooks recommend using copper rather than stainless steel, purportedly because the action of the whisk in a copper bowl sets up electrostatic forces that help the whites whip faster. In "The Physics and Chemistry of the Lemon Meringue Pie," a definitive article on meringue science published in *Scientific American*, June 1981, Jearl Walker describes his unsuccessful efforts to detect an electric field in a bowl of egg whites as he whipped them. Walker was not able to determine whether copper really offers any advantages over stainless steel, but did recommend against aluminum bowls, since the aluminum tends to discolor the whites.

Finally, a little egg white physics. The egg whites start out clear; most of the light that hits the whites is transmitted through them to the bowl. As you start beating the whites however, the trapped air bubbles become large enough to scatter light and some of the light is scattered back into your eye. This scattering increases as more and more bubbles are formed until the mixture looks bright white. If you look at a meringue with a magnifying glass, you can see that the material is still transparent microscopically, even though it appears white in the conglomerate. □

To Do and Notice: The Annotated Lemon Meringue Pie

Lemon Meringue Pie

Meringue pie has a reputation as a temperamental concoction, difficult to perfect. If you would like to experiment with meringue, you can try making your own lemon meringue pie with the recipe below. Follow it closely and your experiment will be extremely edible.

Meringue

Carefully separate **two egg whites** from their yolks. In a greasefree metal bowl, whip the whites until frothy. Whipping egg whites causes the proteins to bond with other protein molecules and trap the air bubbles. Since fat or grease interferes with the bonding between proteins, you must be sure to separate the fatty yolks from the whippable whites. For best results, the eggs should be at room temperature, since cold egg whites are too viscous to incorporate the air bubbles needed for a fluffy meringue.

When the whites are frothy, beat in **¼ teaspoon cream of tartar**. Cream of tartar is an acid. Some meringue recipes substitute vinegar, another acid, for the cream of tartar. Why add acid? The proteins in whipped egg whites have a net negative charge. Since similar charges repel each other, this negative charge interferes with bonding between proteins. In the egg white mixture, molecules of acid dissociate into positively and negatively charged ions. These ions cluster around the charged sites on the protein, reducing the net charge on each protein and making it easier for the proteins to bind together.

Continue whipping until the whites are stiff but not dry. They should stand in peaks that lean over slightly when you remove the beater.

Gradually beat in **four tablespoons powdered sugar** and **½ teaspoon vanilla**. If you add sugar before whipping, the sugar removes water from the protein mixture and makes the liquid more viscous, which makes incorporating air bubbles more difficult.

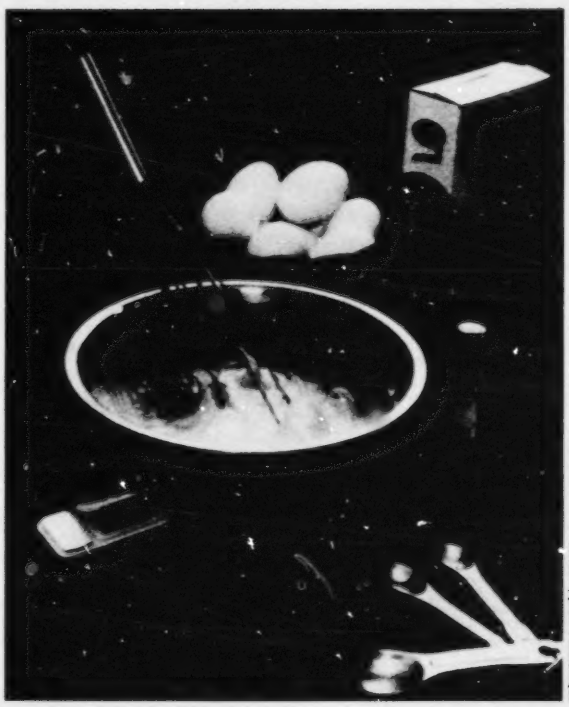


Photo by Joan Ventricque

Filling

In the top of a double boiler, mix **one cup sugar**, **six tablespoons cornstarch**, and **⅛ teaspoon salt**. Gradually add **two cups water or milk**. By mixing the cornstarch with sugar before you add the liquid, you prevent lumps, the bane of any maker of puddings or pie fillings. Cornstarch, the ingredient that makes the filling thick, is made up of granules, stratified layers of starch around a nucleus. When you heat cornstarch (or any other starch) in liquid, the starch granules swell dramatically as they absorb up to 25 times their weight in water. If you were to dump a teaspoon of starch into hot water, the outer granules in the clump would absorb water first, swell up, and block the access of liquid to the starch granules within the lump. By dispersing the cornstarch in the sugar, you separate the starch granules with grains of sugar and prevent them from lumping together.

Cook, stirring constantly, over simmering water for eight to twelve minutes or until thick. The liquid becomes thicker as the starch granules swell. You must handle hot filling gently, since rapid stirring can rupture the bloated granules and thin the filling.

Remove from heat. Pour a little of the hot mixture into **three beaten egg yolks**. Beat this, then add to the mixture in the double boiler. Cook for five more minutes. By beating the egg yolks, you make their proteins unravel from their natural coiled state. The fat in the yolks prevents the formation of an extensive protein network like the one formed by the egg whites, but the proteins do link up and form something of a mesh. By whipping the mixture, you trap air bubbles, which help lighten the filling.

Remove from heat and beat in **three tablespoons butter**, **⅓ cup lemon juice**, and **two teaspoons grated lemon rind**. Cool by stirring gently to release steam. Pour into a prepared pie shell. As the filling cools, attractive forces between starch molecules cause them to join together to form a gel.

Cover with meringue and bake at ten to fifteen minutes at 350°F. The baking temperature and time will affect the consistency of your meringue. At higher temperatures, the air bubbles trapped in the meringue expand more quickly and the meringue does not have as much time to dry and stays chewier. A longer baking time at a lower temperature will give you a crisper, drier meringue. □

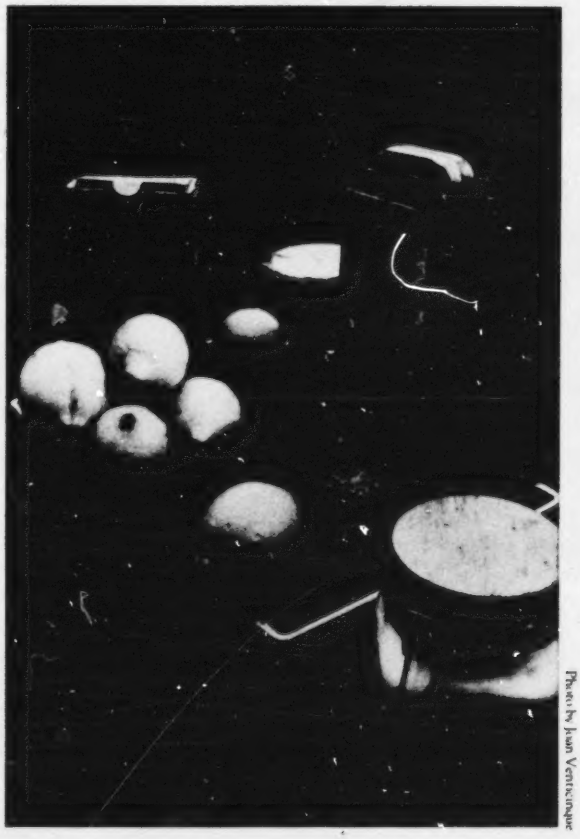


Photo by Jean Ventenaar

To Do and Notice: Taking an Egg for a Spin

by Rob Semper

A little knowledge of physics can help you decide whether that innocent egg sitting in the refrigerator is really hardboiled and ready for your lunch bag, or whether you will be sorry when you try to shell it at your desk.

Select two fresh uncooked eggs from your refrigerator and boil one for about 15 minutes according to the instructions in "The Culinary Alchemy of Eggs."(See page 11).

Put the two eggs on your kitchen table (or any hard surface) and give them a spin. Notice that one continues to spin easily after you get it started, but the other quickly comes to a stop. The egg that keeps spinning is the hardboiled egg, a fact you can verify at the end of your experimentation.

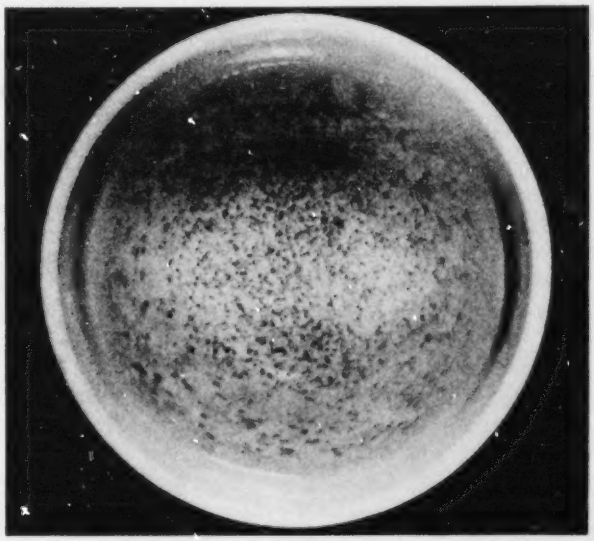
Give both eggs a number of twists to get them really spinning. Stop them by grabbing them momentarily and releasing them immediately. Notice that the uncooked egg starts to spin again after you let go, while the hardboiled egg remains motionless.

In a solid material, the bonds between the atoms are strong enough that a push at one point of the solid is transmitted almost instantly to the entire solid. But in a liquid, the bonds between the atoms are much weaker and the molecules can slip past each other. A push on one part of the liquid is transmitted at a slow rate to the liquid as a whole, and some of the energy is dissipated opposing the drag or friction in the fluid.

When you spin an egg, the motion you give the shell is transferred to the interior of the egg. In the case of the hardboiled egg, which is solid, the rotational motion is transmitted directly to the whole egg, and it spins freely. All of the rotational energy that you are applying goes into the spinning of the whole egg.

An uncooked egg is a semi-viscous liquid contained by the shell. When you spin an uncooked egg, the motion of the shell affects only the fluid right next to the shell, dragging it along. The fluid in the center initially stays at rest. The uncooked egg quickly stops spinning because the stationary fluid near the center drags the fluid near the edge to a halt, and that fluid drags the shell to a stop. The combined weight of the shell and the moving fluid near the edge is quite light and the drag of the central fluid is enough to stop the rotation.

When you continue to add rotational energy by constantly spinning the egg, the moving fluid near the shell begins to drag along the fluid next to it until all of the fluid is rotating along with the shell. The slippage or drag of the fluid does soak up extra energy, however, which is why you have to spin the uncooked egg longer to get it to keep spinning after you let go. If you try to stop the uncooked egg after it is spinning, you can stop the shell, but the interior fluid keeps on spinning. This rotation can restart the shell spinning when you let it go again.



Nutmeg floating on the surface of a bowl of water moves with the water. If you spin the bowl, the water and the floating nutmeg at the bowl's center remain stationary. The nutmeg at the edge of the bowl moves as the water is dragged along by the spinning bowl. The movement of the liquid inside a raw egg when you start it spinning is similar to the movement of the liquid in the spinning bowl. The liquid in the egg's center remains stationary; the liquid adjacent to the eggshell moves with the shell.

You can see this effect if you fill a round mixing bowl with water and sprinkle the surface with some cinnamon, nutmeg, or any powder that will float. Grab the edge of the bowl and give it a spin. Notice that the water stays quite stationary at first except for the water near the edge. The longer you spin the bowl, the more the water inside spins. You are continually adding rotational energy to the bowl and the water, but some of this energy is dissipated by the viscous drag of the water. If you stop spinning the bowl, the water keeps on spinning for quite a while until it loses its energy by dragging along the side of the bowl. □

On the Rise

by Linda Dackman

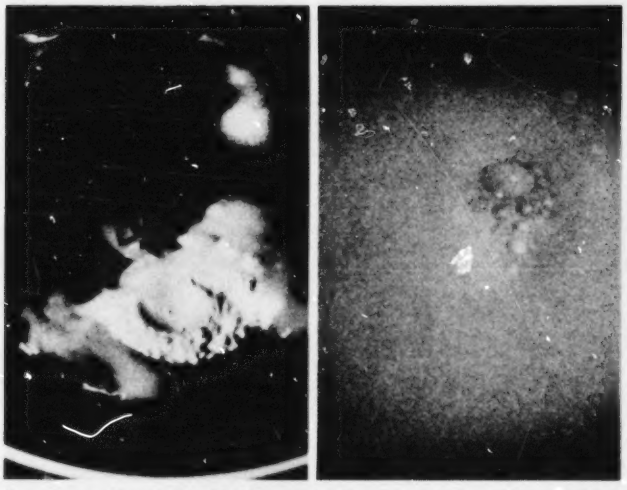
My early attempts at baking were pagan rituals, childish delights in the sensual concocting and working of dough, and swallowing it — no matter what the taste — hot and steamy out of the oven. Like the first bread bakers, the Egyptians, I stood in awed admiration should the product of my labors expand once I had entrusted it to supernatural forces. And like the Egyptians, I did not know the chemical science of baking, although it was discovered in the seventeenth century when Van Leeuwenhoek first saw yeast cells under his microscope. As a child of the twentieth century, my image of the oven-altar gave way to that of the kitchen-laboratory within a decade and a half. But make no mistake, discovering the chemistry of baking for me was merely a tool in my still abject worship of hot steamy bread.

As a child I tried to bake yeast bread and failed. I tenderly set my dough to rise on the top of my bedroom radiator, next to a leaky window in the dead of winter. My yeast dough half steamed, half froze. It slumped there for hours, a leadened mass destined never to rise.

For years after, I limited myself to quick-bread chemistry, letting double-acting baking powder provide the carbon dioxide needed to create airpockets in my batters and doughs. Baking powder is essentially a blend of an acid (calcium acid phosphate, sodium aluminum sulfate, or cream of tartar) and an alkali (sodium bicarbonate, also known as baking soda). When water is added to this mixture, a chemical reaction occurs producing carbon dioxide. Once the bread is in the oven, heat furthers the process of carbon dioxide production, expands the trapped gas and air, and also creates steam. All these factors combine to make baking chemically leavened breads foolproof.

Usually.

Once, when I was making maple muffins, I used very old baking powder. Impotency is not a myth when you're talking about advanced age in leavening chemicals. The baking powder simply did not expand the batter. I have since learned to periodically test baking powder by conducting a simple chemical experiment. Pour one-quarter cup of hot water over one-half teaspoon baking powder. The mixture should bubble as carbon dioxide is released. This is essentially a replication of high school class experiments where water poured over a dry acid and alkali mixture also produces carbon dioxide bubbles. The fresher the baking powder, the more active the response: a weak reaction and your



You can test the potency of baking powder by pouring ¼ cup of hot water over ½ teaspoon of baking powder. If the baking powder is potent, a chemical reaction will produce carbon dioxide and the mixture will bubble.

tired baking powder will produce a tough textured bread.

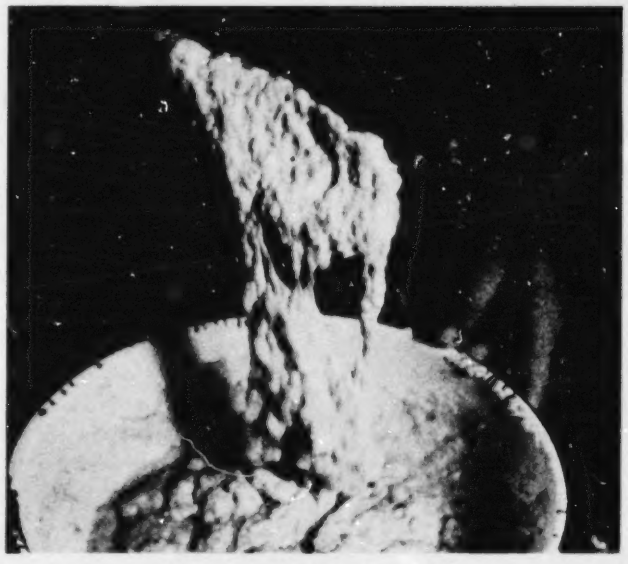
On another occasion, I tried a different small experiment. I substituted buttermilk for sweet milk. They're both milk, I thought, and they measure the same. The slightly sour flavor should be interesting. My experiment created another leadened mass. Buttermilk upset the recipe's chemical balance. The acids and alkalis are carefully balanced in bread recipes and must always be in proper proportions for the essential release of carbon dioxide in the dough. The uncalled-for addition of buttermilk increased the acidity of the mixture and thereby reduced carbon dioxide production. If you ever get a craving for buttermilk in your bread, compensate for the extra acid by the addition of baking soda — an alkali. Better yet, find a recipe that calls for buttermilk in the first place.

Still, my quick bread embarrassments were only impersonal flops. No serious investment of time, no nursing the yeast, no testing the water on the inside of the wrist as though it was for baby's bath, no critical kneading, no anxious glances (expectant fatherlike) under the damp cloth to see if the bread has risen. Yeast baking on the other hand is very personal. It is conceiving, being pregnant and giving birth all in one afternoon.

Like any good parent, I wanted this offspring to have the best from the start. I headed for the supermarket to buy baker's flour, a hard flour especially suited for breadmaking because of its high gluten content. Among the many proteins in flour, gliadin (which becomes gooey in water) and glutenin (which becomes rubbery) will band together when you add water and force them together with kneading. The product of their union is gluten, a protein compound that forms a cohesive network of elastic strands — a three dimensional structure that holds the dough together and yet is elastic so that the dough will stretch.

Every package of flour I found at the supermarket was labeled "All Purpose," a combination of the hard flour that I needed and the soft flour that is best for cakes. I was forced to compromise, and I feared for my as yet unmade bread. Would the structure hold in the face of the developing carbon dioxide gas? Then it struck me. I had bigger problems. I had never before gotten yeast to produce even one molecule of carbon dioxide.

Yeast, or *Saccharomyces cerevisiae*, are temperamental minute one-cell fungi that can be lackadaisical or overly enthusiastic depending on the temperature of the water they are mixed in and, eventually, the temperature of the dough. The ideal water temperature for yeast growth is between 105° and 110°F, just a little warmer than body temperature. If the water is too cool, a dough-harming substance diffuses out of the yeast; too hot and the yeast gives up with heat prostration and stops fermenting. The dramatic effect of yeast is that it ferments sugar (or starches which the yeast can convert to glucose, a simple sugar) into gaseous carbon dioxide and alcohol. As with breads baked with baking powder, the carbon dioxide, along with trapped expanding air and steam, leavens the bread.



When you knead bread, you make gluten, the protein compound that gives bread its elasticity.

You can test the vitality of yeast by mixing the yeast with a teaspoon of sugar in ¼ cup of warm water. If the yeast is alive, it will consume the sugar and produce carbon dioxide bubbles.

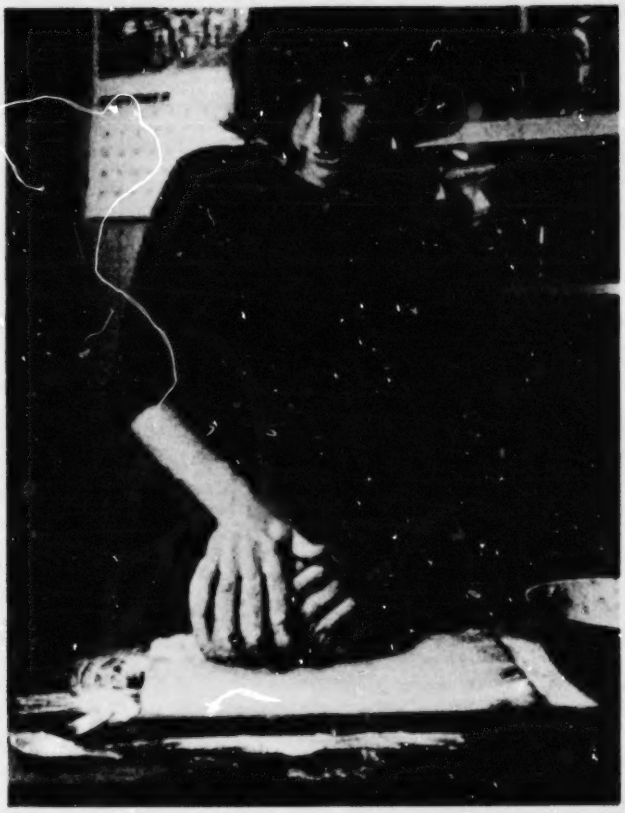
To be safe, I tested the vitality of my yeast, feeding them one teaspoon of sugar in a solution of one-quarter cup warm water. After five minutes they began bubbling. So I couldn't pretend I had been sitting around for two hours waiting for my dough to ferment and all the time the yeast were Dead on Arrival.

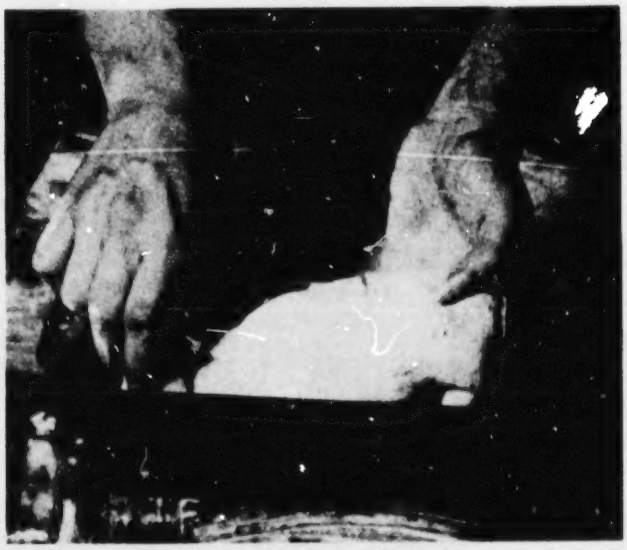
A chilling fact, however, was that they might still die at any time, particularly if I introduced them into a dough that was too cold to foster yeast growth. A temperature range of 80° – 95°F is considered best for leavening bread. I had all my ingredients at room temperature, a temperature I artificially induced in my postage-stamp-sized kitchen by turning the oven on about three hours early. I closed the windows and the doors. Yeast don't like drafts either. I could have raised orchids in that environment but could I raise dough? Was it too hot or too cold? Had I liquidated the yeast? Had they expired from heat prostration?

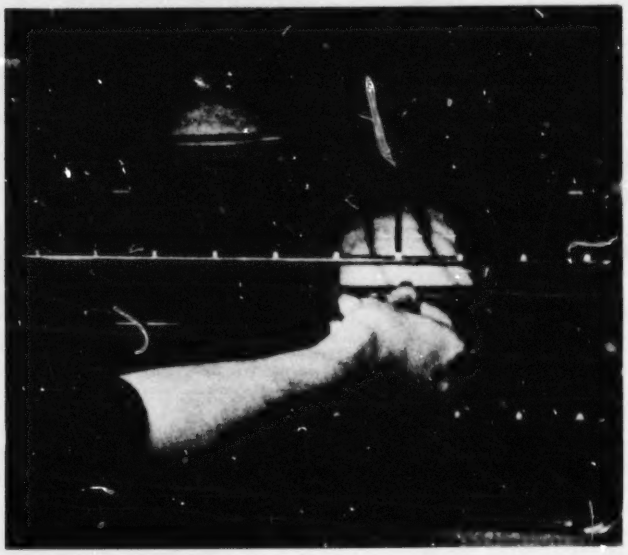
The dough rose! Cigar anyone?

Resting casually during the dough's second rising, I pulled out my baking pans — an old glass one from my Aunt Molly, a shiny aluminum one from Safeway and a dull, dark carbon steel one from my last visit to the Sausalito fleamarket. I did some quick thinking, considering what would happen if I took a walk in the sun on a hot day, first in a black dress, then in a white one and finally in nothing at all. What I wore would affect the amount of light energy that I reflected or absorbed and therefore the speed at which I warmed up and baked in the sun. Black absorbs energy; white reflects it. My recipe called for a dark pan, no doubt because its black surface would absorb more radiant energy from the oven walls. The shiny surface of the aluminum pan would reflect heat and cook my bread too slowly. The transparent glass would allow radiant heat to pass directly to the dough, absorbing little of the energy and thereby cooking the bread too quickly. I ran out and bought another dark pan before the end of the second rising. I could also have solved the problem by reducing the temperature and cooking time for the glass pan or increasing both those variables for the shiny pan — except that I couldn't simultaneously cook each of the loaves if they required such different conditions.

The simultaneous baking of several bread loaves holds one final snare: the physics of convection currents. Convection currents are the pattern of movement by which heat rises and then discharges to walls, racks, pans, and finally to the bread in the oven. Pan placement affects the







circulation and movement of currents and contributes to the quality of baking. Pans which are placed evenly from the walls of the oven and staggered on different shelves will cook evenly.

Looking back, breadbaking is experimentation with biology (yeast, those single-cell fungi), chemistry (carbon dioxide production, gluten production and the balance of alkali and acids) and physics (convection currents and the relationship between incident radiation and baking pan materials). It is a satisfying sweet–smelling investigation of science, a rare opportunity to measure and intuit like the greats. I feel a cross between an Egyptian on the Nile, Betty Crocker and Dr. Frankenstein, all the more disciplined in my work by the humbling prospect of having to literally eat my mistakes. □

To Do and Notice: Whole Wheat Bread

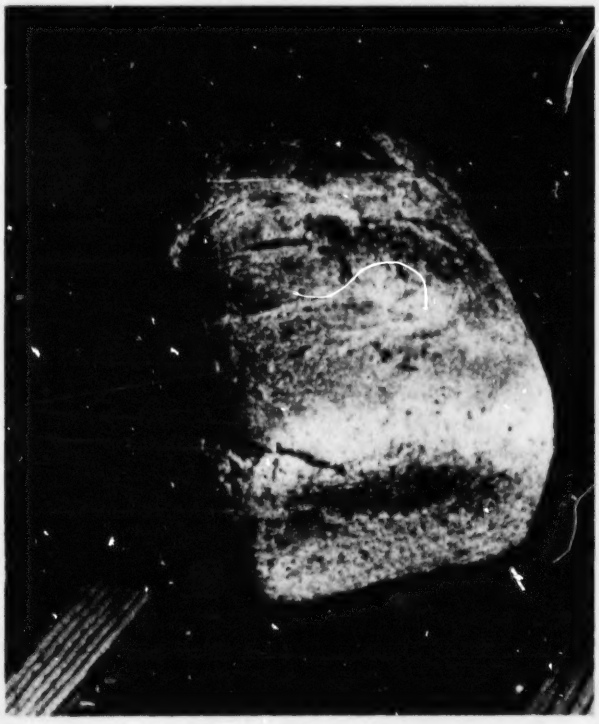
For those who would like to duplicate Linda Dackman's kitchen experimentation, here is her recipe for yeast bread.

Remember that the temperature of the ingredients, the water, and the kitchen are important to the health of your bread. Linda advises that you test the water on your wrist, as you would the milk in a baby's bottle, to make certain it is just a little warmer than body temperature: warm enough to activate the yeast but not hot enough to kill it.

Linda's recipe calls for kneading the bread twice. Kneading forces together two proteins — gliadin and glutenin — to make gluten, the protein compound that gives bread dough its elasticity. You encourage gluten formation with kneading. In preparing a pie crust, which you want to be flaky rather than elastic, you handle the dough very little and use more shortening, which interferes with gluten formation.

Each time you knead the bread, you crush the bubbles produced by the yeast, squeezing out excess carbon dioxide and making each large bubble into several small ones to produce a fine-textured loaf.

Though this is a recipe for whole wheat bread, it calls for all-purpose white flour as well as whole wheat flour. Since white flour contains more gluten per weight than whole wheat flour, the addition of white flour to the recipe makes for a more elastic, lighter loaf.



Whole Wheat Bread

1 pkg. active dry yeast
¼ c lukewarm water
¼ c sugar
2 t salt
2 T shortening
1 c milk
1 c boiling water
2½ c unsifted all-purpose flour
3 c unsifted 100% whole wheat flour

Dissolve yeast in lukewarm water. In another bowl, mix sugar, salt, shortening, milk, and boiling water. When milk mixture is lukewarm, add yeast mixture and all-purpose flour. Slowly add the whole wheat flour. When the dough is stiff enough to handle, turn onto a floured board and knead until dough is smooth and elastic. Place in an oiled bowl, cover, and let rise until doubled in bulk. Knead and let rise again. Shape into two loaves, place in greased 9×5 pans and let rise until doubled in bulk. Bake at 400°F for 45 minutes or until golden brown. You can test the bread for doneness by tapping the loaf with your fingers; when the loaf sounds hollow, it's done. Remove loaves from pans and cool on wire racks. □

References and Related Articles

If you would like to learn more about the science of cooking, we suggest the following books and articles.

Cobb, Vicki. **Science Experiments You Can Eat.** New York: Lippincott Company, 1972.
An excellent activity book for children.

Grosser, Arthur E. **The Cookbook Decoder, or Culinary Alchemy Explained.** New York: Beaufort Books, Inc., 1981. (Also available in paperback. New York: Warner Books, Inc., 1983.) An entertaining book, which provides explanations of the scientific logic underlying recipes.

Grosser, Arthur E. "The Culinary Alchemy of Eggs." **American Scientist,** March-April 1983.
Grosser's original article includes a section on "Egg Physics" that we did not reprint with the rest of the article. The "Letters to the Editor" column of the May-June issue of **American Scientist** contains several reactions to Grosser's article in general, and this section in particular.

Hillman, Howard. **Kitchen Science: A Compendium of Essential Information for Every Cook.** Boston: Houghton Mifflin Company, 1981.
An informative book, which answers questions on cooking methods, cooking equipment, foods, and food storage.

Rombauer, Irma S. and Becker, Marion Rombauer. **Joy of Cooking.** Indianapolis, Indiana: The Bobbs-Merrill Company, Inc., 1964.
A cookbook for the completist, which includes extensive information on ingredients and cooking techniques.

Tannahill, Reay. **Food in History.** New York: Stein and Day, Publishers, 1973.
A comprehensive account of the history of food and cooking.

Walker, Jearl. "The Amateur Scientist: The physics and chemistry of the lemon meringue pie." **Scientific American,** June 1981.
The definitive article on the science of lemon meringue pies.

Walker, Jearl. "The Amateur Scientist: The physics and chemistry of a failed sauce bearnaise." **Scientific American,** December 1979.
A description of the scientific principles determining the success or failure of a difficult culinary concoction.

Zubrowski, Bernie. **Messing around with Baking Chemistry.** Boston: Little, Brown and Company, 1981.
An excellent activity book for children.

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